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Tectonic significance of Late Precambrian calc-alkaline and alkaline magmatism in Saint Katherina Area, Southern Sinai, Egypt

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ABSTRACT

Two magmatic rock suites are distinguished in the Late Precambrian basement of the Southern Sinai (NW Arabian-Nubian Shield, Egypt), namely (a) a calc-alkaline suite, and (b) an alkaline suite. The former includes Rutig Volcanics, quartz-diorite, quartz-monzonite and monzogranite, while the latter includes Katherina Volcanics and A-type granites. The minerals and textural features (kink, decussate and foliated textures) of the quartz-diorite reveal that it was subjected to deformation and thermal metamorphism. The Rutig Volcanics and quartz-diorite represent subduction related I-type magma, generated from anatexis of older crust with contribution of mantle-wedge magma. The quartz-monzonite and monzogranite are evolved from hybrid magma due to injection of the partly crystallized granitic magma by more basic melts. The mineralogical and geochemical characteristics of these granites indicate a mildly alkaline character and belonging to transitional magma type on the borderline between the calc-alkaline and alkaline magma. The mafic microgranular enclaves (MME) in the quartz-monzonite and monzogranite represent cooled globules from a dioritic magma mingled with the partly crystalline granitic magma. The association of rapakivi texture with the MME confirms the genetic link between the rapakivi texture and magma mixing. The overall characteristics of the Katherina Volcanics and A-type granite are consistent with within-plate tectonic setting. The Katherina Volcanics are derived from a crustal source with a mantle contribution, whereas A-type granites represent residual melts derived from deeper magma chamber through extreme fractional crystallization process.

KEYWORDS **Rutig. Katherina. Magma mixing. A-type granite.**

INTRODUCTION

The Precambrian basement rocks exposed in Saint Katherina area (Southern Sinai), including the studied area, have been studied by many authors (e.g. Eyal and Hezkiyahu, 1980; Mohanna, 1988; Shendi, 1988; Soliman, 1992; Hashad et al., 1999; Gharib and Obeid, 2004; Katzir et al., 2007). The area under consideration, Wadi Sibaiya, lies at about 5 km to the northeast of Saint Katherina Town in the high mountainous region of central South Sinai (Fig. 1). Wadi Sibaiya area was chosen because all rock units in Saint Katherina area crop out there, and because previous studies created considerable controversy on the origin and tectonic setting of the basement rocks at Wadi Sibaiya. Eyal and Hezkiyahu (1980) considered that the Katherina Pluton (including the studied part) was emplaced during one intrusive episode of alkaline affinity. Whereas Soliman (1992) concluded that the granitoid rocks in the present area have a wide range of geochemical properties suggesting emplacement in a volcanic-arc as well as a within-plate tectonic settings. He attributed the within-plate characters to crustal contamination of mantle derived magmas. Moreover, earlier studies did not focus on the mafic microgranular enclaves (MME) in the studied area. Therefore, this work focus on the field occurrence and features of MME that are relevant to magma mixing between two contrasting mafic and felsic magmas. The major aim of this paper is to improve the understanding of the history of the basement rocks and to clarify the relationship between the calc-alkaline plutonic and volcanic rocks and the younger alkaline igneous rocks in the Saint Katherina area.

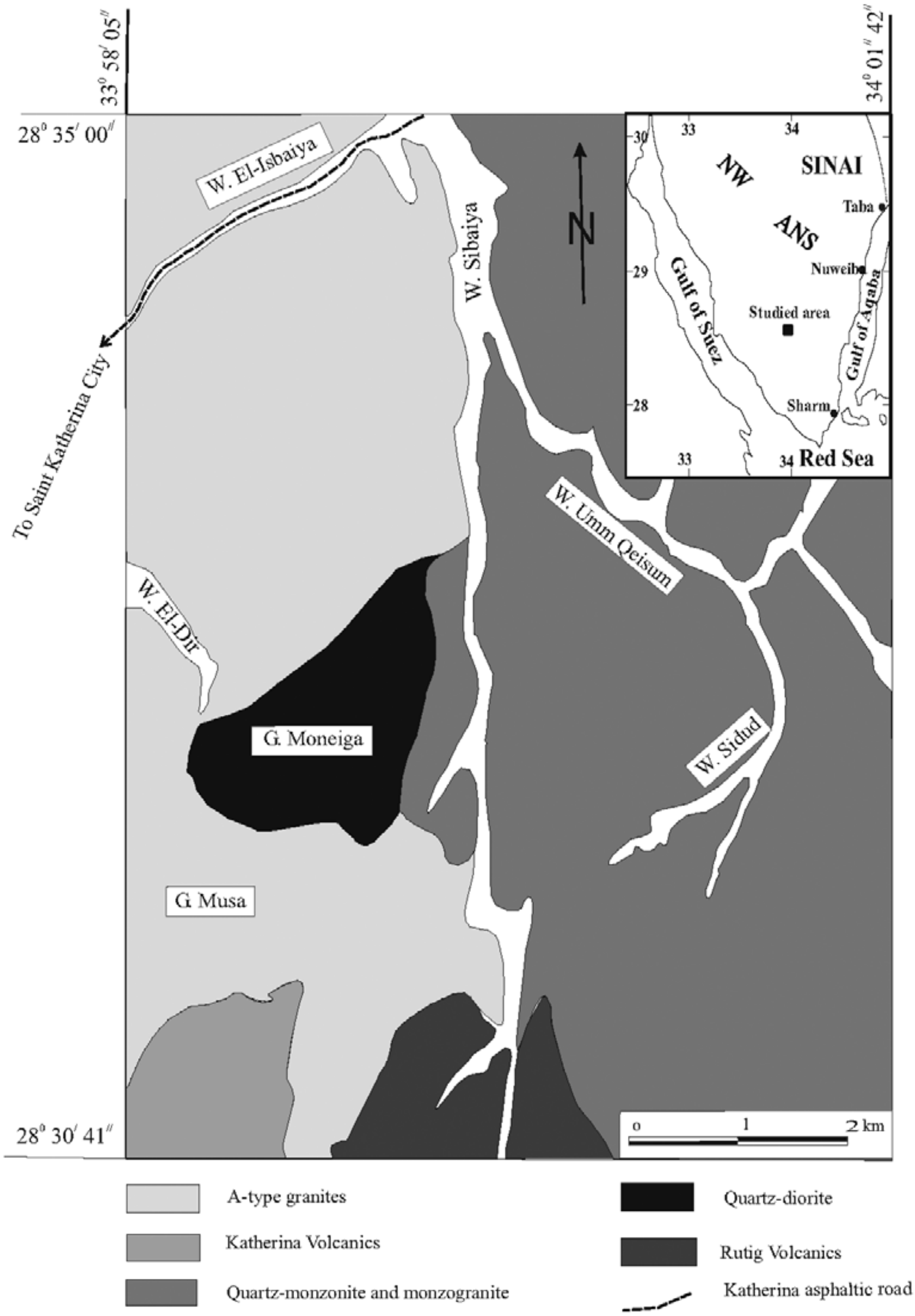

FIGURE 1 | **Geological map of Wadi Sibaiya area (modified after Soliman, 1992).**

GEOLOGICAL SETTING

The area of Wadi Sibaiya is bounded by latitudes 28º 30' 41" and 28º 35' 00" N and longitudes 33º 58' 05" and 34º 01' 42" E (Fig.1). This area is dissected by several wadis, including Wadi El-Isbaiya, Wadi El-Dir, Wadi Sibaiya, Wadi Umm Qeisum and Wadi Sidud, forming a rectangular drainage pattern indicating that the area is structurally controlled by faults.

The basement rocks of Sinai represent the northwestern extremity of the Arabian-Nubian Shield (ANS; Fig. 1). The formation of the ANS during the Pan-African Orogeny represents one of the most intensive episodes of continental crust formation on Earth (Reymer and Schubert, 1984, 1986; Bentor, 1985; Stern, 1994; Stein and Goldstein, 1996). The geological history of the ANS has been divided into four main phases (Bentor, 1985): 1) Oceanic ophiolites phase (~1000 Ma ago) that is represented by pillowed basalts and their plutonic equivalents; 2) island-arc phase (~950-650 Ma ago) that is dominated by andesitic volcanism and (quartz-) dioritic intrusions; 3) batholithic phase (~640-590 Ma ago) that is represented by subaerial, medium to high-K calc-alkaline volcanics of andesite to rhyolite composition and their plutonic equivalents; and 4) an alkaline phase (~590-550 Ma ago) that comprises intraplate alkaline, high level granites and syenites and their volcanic equivalents (Katherina Province). Some authors doubt about the presence of phase I and Phase II in Sinai (Bentor, 1985; El-Gaby et al., 1990).

According to the most recent classification of the basement rocks of Egypt (El-Gaby, 2005), the Egyptian basement complex splits into four groups: 1) Pre-Pan-African rocks comprising deformed granites (including Shaitian granites), migmatites, gneisses and high-grade Barrovian-type metamorphites, 2) Pan-African ophiolite and island arc assemblages thrust onto the old continent causing deformation and cataclasis in the over-ridden infrastructural rocks, 3) Pan-African Cordillera stage comprising calc-alkaline gabbro-diorite complexes, Dokhan Volcanics, Hammamat sediments, calc-alkaline granite series, together with olivine gabbro and related rocks, and 4) post orogenic to anorogenic alkaline to peralkaline silicic magmatism including alkali feldspar granites, syenites and alkali rhyolites.

THE MAGMATIC SUITES

All the rock units in Saint Katherina area are represented in Wadi Sibaiya and distinguished into calc-alkaline and alkaline suites. The former comprises Rutig Volcanics, quartz-diorite, quartz-monzonite and monzogranite, whereas the latter comprises Katherina Volcanics and A-type granites. The field relationships between the different rock types in the Wadi Sibaiya area are giveng in the following sections.

Calc-alkaline suite

Rutig Volcanics

They are exposed in the southern part of the mapped area and extend beyond the southern boundary. They are intruded by quartz-monzonite and A-type granites. These volcanics constitute a thick volcano-sedimentary succession made up by lava flows that range from intermediate to acid and pyroclastics alternating with conglomerates and arkose (Eyal and Hezkiyahu, 1980; Eyal et al., 1994). The intermediate volcanics are represented by andesite, while the acid volcanics included dacite, rhyodacite and rhyolite. Abdel Maksoud et al. (1993) and Abdel Khalek et al. (1994) distinguished the Rutig Volcanics into older and younger volcanics, which are comparable to the ophiolitic Older Metavolcanics (OMV) and the island arc Younger Metavolcanics (YMV) of Stern (1981) in the Eastern Desert of Egypt. Oweiss (1994) described the subduction-related volcanics at Saint Katherina area (including Rutig Volcanics) as slightly metamorphosed Dokhan Volcanics which carry bands of banded iron formation. The upper unit of Rutig Volcanics gave a Rb-Sr age of 587±9 Ma (Bielski, 1982), which is comparable to the age of the calc-alkaline subduction-related volcanics of Phase III (Bentor, 1985).

Quartz-diorite

It is dark gray in colour and occupies terrains of moderate to low relief. It is massive in the center of the pluton, but grades into foliated quartz-diorite at the margins, the so-called border quartz-diorite. Also, a zone of hybrid rocks, about 3 meters wide, is developed along the contacts between the quartz-diorite and quartz-monzonite. No age dating has been performed for the quartz-diorite, but field relations indicate that it is older than the quartz-monzonite, monzogranite and A-type granites.

Quartz-monzonite

It has gradational contacts with monzogranite and the both rock types have same appearance in the field and on the aerial photographs. We can not distinguish between them on the geological map. Age dating of these rocks is not available. Quartz-monzonite is pale gray to bluish gray in colour, highly porphyritic and contains few mafic microgranular enclaves (MME). Rapakivi texture is observed in the hand specimens, where a thin white plagioclase mantle surrounds the K-feldspar phenocrysts. The quartz-monzonite has undergone extensive alteration, especially in the vicinity of faults and along the contacts with the A-type granites, probably caused by hydrothermal solutions emanating from the alkaline phase. This alteration was distinguished into kaolinization, silicification, sericitization and propylitization (Shendi, 1992).

Monzogranite

It is highly porphyritic where the K-feldspar phenocrysts are frequently rimmed by a thin plagioclase layer forming a mesoscopic rapakivi texture. It contains many fine grained mafic microgranular enclaves (MME) (Fig. 2A). The MME are ellipsoidal to spherical in shape with lobately outlines; some possess irregular outlines. They range in size from 5 to 25 cm long and the elliptic MME are disposed vertically. Rarely, the margins of the MME show sings of hybridization and the feldspar crystals gather along the border between the enclaves and monzogranite. Few MME carry large plagioclase and K-feldspar phenocrysts from the enclosing monzogranite.

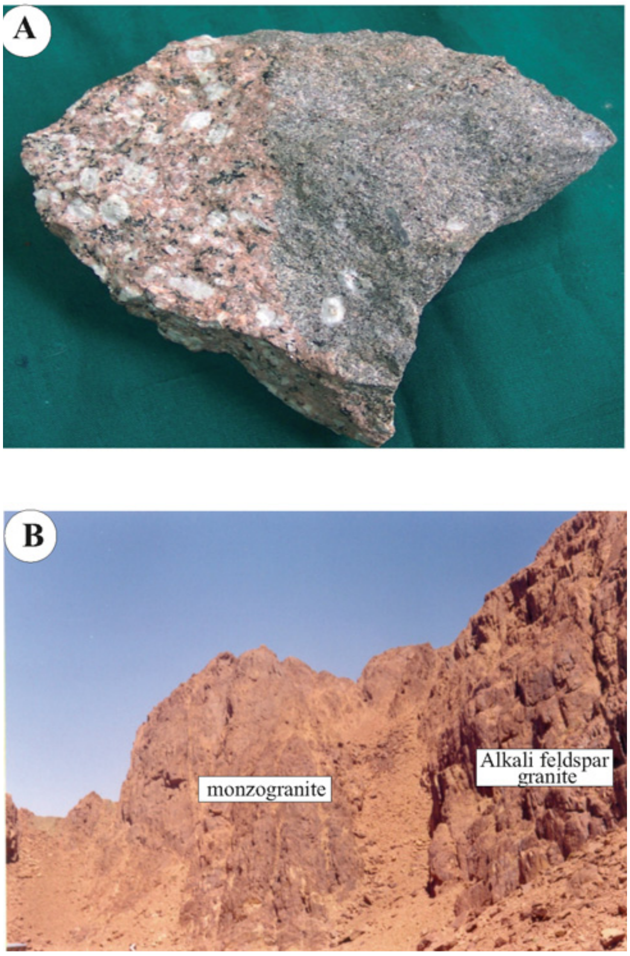

FIGURE 2 **(A) Hand specimen showing the contact between MME and monzogranite. Note the signs of assimilation and the presence of xenocrysts derived from the host rock. (B) Alkali feldspar granite intruded into monzogranite.**

Alkaline suite

Katherina Volcanics

They crop out at Gebel Musa in the southern part of the studied area as roof pendants and extend beyond the southern boundary of mapped area. They are intruded by A-type granites and show sub-horizontal contacts. The Katherina Volcanics comprise alkali rhyolite lava flows and pyroclastics. These volcanics were dated to 578±6 Ma at Gebel Katherina (Bielski, 1982).

A-type granites

They represent the youngest rock unit in the studied area and intruded the older rock units with sharp contacts (Fig. 2B). These granites were emplaced at shallow depth, as evidenced by fine-grained and porphyritic marginal zones. A-type granites are represented by syenogranite which grade vertically into alkali feldspar granite. The transition from syenogranite to alkali feldspar granite is poorly discernible in outcrops and only recognized by the decrease in plagioclase content. A-type granites are scarcely intruded by dykes and devoid of xenoliths. They are medium to coarse grained and characterized by pale pink, pink and red colours. The contacts of the alkali feldspar granite with the other rock types are characterized by the presence of pegmatitic pockets and veins, which led Soliman (1992) to describe this granite as pegmatitic granite. The pegmatitic pockets and veins might represent segregations along fractures in the solidified outer margin at increased moderate water and volatiles concentrations (Llambia et al., 2003). In the studied area, A-type granites, quartz-monzonite and monzogranite are grouped as Iqna granite by Bentor et al. (1972). In South Sinai, the Iqna granites and the alkaline/peralkaline granites possess characteristics of the within-plate A-type granites (Azer, 2007). A-type granites of Katherina area gave Rb-Sr ages of 560±10 Ma (Bielski, 1982) and 593±16 Ma (Katzir et al., 2007). These ages complied with the field relations indicate that the A-type granites are the youngest rock unit in the studied area.

PETROGRAPHY

Twenty-one representative samples of the plutonic rocks representing calc-alkaline and alkaline suites were point-counted for modal analyses. The modal analyses are represented in Table 1 and plotted on the QAP modal diagram of Streckeisen (1976). On this diagram (Fig. 3), the plutonic rocks of the calc-alkaline suite are classified as quartz-diorite, quartz-monzonite and monzogranite,

TABLE 1 | **Representative modal analyses of the studied plutonic rocks.**

Rock type		Sample No.	Minerals					
			Quartz	K-feldspar	Plagioclase	Biotite	Amphibole	Accessories*
Alkaline suite	Alkali feldspar gra	Ag-1	29,6	65,2	3,5	1,0	0,0	0,7
		Ag-6	31,5	60,9	5,7	1,4	0,0	0,5
		Ag-11	38,5	57,2	2,8	0,9	0,0	0,6
		Ag-15	32,0	64,0	1,5	1,2	0,0	1,3
	Syenogranite	Sg-2	35,7	50,1	11,6	1,7	0,0	0,9
		Sg-3	31,8	51,3	14,5	1,6	0,0	0,8
		Sg-4	32,1	48,9	14,3	3,2	0,0	1,5
		Sg-5	34,1	48,5	12,0	3,6	0,0	1,8
Calc-alkaline suite	Monzogranite	Mon-g-1	27,1	36,2	34,2	1,1	0,3	1,1
		Mon-g-2	29,6	39,7	27,8	1,5	0,5	0,9
		Mon-g-3	25,3	41,6	29,5	1,7	0,4	1,5
		Mon-g-4	31,6	34,3	29,6	1,9	0,0	2,6
	Qz-monzonite	QMZ-1	11,4	32,6	49,8	1,2	1,8	3,2
		QMZ-2	14,2	34,9	43,6	2,1	1,9	3,3
		QMZ-3	18,4	41,7	35,7	1,8	1,1	1,3
		QMZ-4	17,2	30,4	46,3	1,9	1,6	2,6
		QMZ-5	9,7	30,9	51,5	1,1	2,0	4,8
	Qz-diorite	QD-1	15,2	3,6	58,8	4,2	10,3	7,9
		QD-2	4,6	2,5	65,1	5,6	13,0	9,2
		QD-3	14,4	4,8	57,6	4,9	10,5	7,8
		QD-4	9,4	6,1	54,9	5,6	15,9	8,1

* Accessories include Fe-Ti oxides, apatite, zircon, sphene, allanite and secondary minerals.

whereas those of the alkaline suite are classified as syenogranite and alkali feldspar granite. The petrographic descriptions of the different rock types in the Wadi Sibaiya area are given in the following sections.

Calc-alkaline suite

Rutig Volcanics

Rutig volcanics, exposed in the studied area, are represented by dacite, rhyodacite and pyroclastics which are intercalated within the Hammamat sediments. Dacite carries plagioclase and few hornblende, biotite and quartz phenocrysts, embedded in a microcrystalline felsic groundmass. Some plagioclase phenocrysts are saussuritized and replaced by albite, epidote, sericite and calcite. Also, chloritization of the mafic minerals and the development of secondary amphibole (actinolite) are observed. Rhyodacite is rather similar to dacite but contains more K-feldspars and quartz phenocrysts and less mafic minerals. Pyroclastics are represented by welded tuffs, which consist mainly of K-feldspars and quartz crystals and crystal fragments embedded in a groundmass of flattened and welded glass shards. The Hammamat sediments are represented by siltstone. It is ill- to well-sorted and consists of angular to sub-rounded grains of quartz and feldspars with rare biotite and opaques.

Quartz-diorite

It is medium grained and possesses a hypidiomorphic granular texture. It is composed mainly of plagioclase and mafic minerals with smaller amounts of quartz and K-feldspars. Plagioclase is the most common mineral and occurs as subhedral tabular crystals, which show normal and rarely oscillatory zoning. Sometimes, it is strongly altered to sericite in the core of the crystals. Some crystals develop myrmekitic outgrowths into neighboring K-feldspars. Quartz occurs as anhedral crystals with sutured outlines and shows undulatory extinction. Some crystals enclose muscovite and mafic inclusions. Mafic minerals comprise biotite and hornblende in variable proportions. Biotite forms discrete anhedral to subhedral flakes and crystal aggregates. It is pleochroic from brown to honey yellow and partially chloritized. Some biotite flakes are kinked due to deformation. Hornblende occurs as subhedral crystals pleochloric in shades of green and olive brown. It is recrystallized into aggregates of actinolite, biotite and chlorite disposed in a criss-cross fashion, i.e. a decussate texture (Fig. 4A). K-feldspars are less common and occur as small perthitic crystals between the other constituents. The accessory minerals are represented by sphene, zircon, Fe-Ti oxides and apatite. The marginal part of the quartz-diorite mass is foliated and biotite content increases at the expense of hornblende.

Quartz-monzonite

It is porphyritic with phenocrysts of plagioclase, K-feldspars and mafic minerals embedded in a medium grained groundmass having the same composition plus

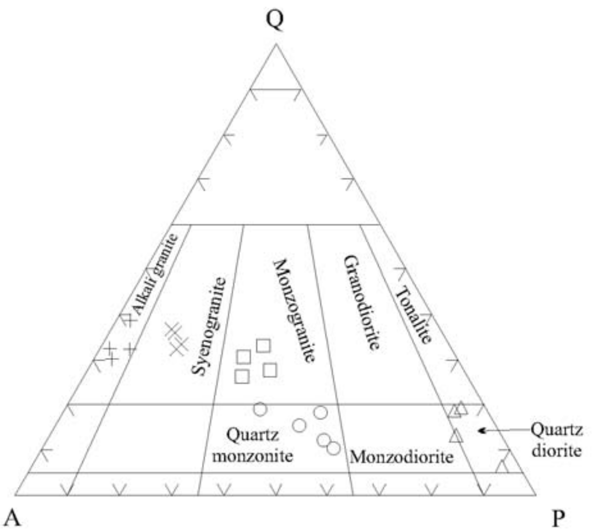

FIGURE 3 | **QAP plot of the modal compositions of the plutonic rocks (Streckeisen, 1976). Symbols of the plutonic rocks used in all the given figures are: Δ =quartz-diorite; O =quartz-monzonite; □ =monzogranite; X=syenogranite; + =alkali feldspar granite.**

quartz. Plagioclase predominates among the phenocrysts and occurs as large zoned, euhedral to subhedral tabular crystals and as small crystals in the groundmass. A few plagioclase crystals have resorbed inner core that was later overgrown by an outer zone. Perthitic orthoclase and/or microcline occur as large equant phenocrysts or as small anhedral crystals in the groundmass. Rapakivi texture is quite rare. Quartz is confined to the groundmass and builds also myrmekitic and graphic intergrowths with feldspars. The mafics are represented by hornblende and biotite. They occur as anhedral to subhedral phenocrysts or as fine anhedral crystals in the groundmass. The accessory minerals are represented mainly by apatite, zircon and Fe-Ti oxides while the secondary minerals include chlorite, epidote and sericite. The environmental scanning electron microscope (ESEM) study, carried out at the Nuclear Materials Authority in Egypt, revealed zoning in the apatite crystals not visible in transmitted light as well as some crystals possess partly resorbed inner part overgrown by a late one.

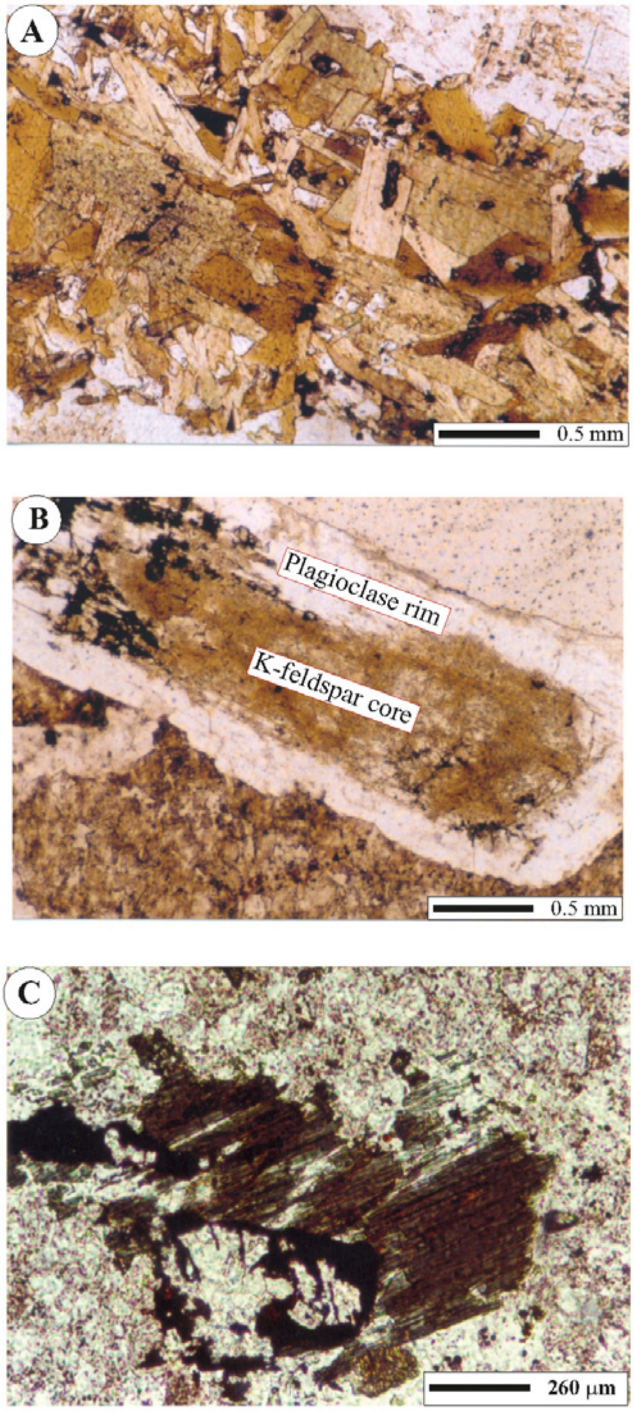

FIGURE 4 | **A) Decussate texture in quartz-diorite (plane light). Note that hornblende recrystallized to an aggregate of actinolite, biotite and chlorite disposed in a criss-cross fashion. B) Rapakivi texture in monzogranite (plane light). C) Alkali amphibole phenocrysts in the rhyolite (crossed nichol).**

Monzogranite

It carries pink phenocrysts of K-feldspars (up to 7 mm long) and white plagioclase phenocrysts (up to 12 mm long) embedded in a fine to medium grained groundmass. The amount of the K-feldspar phenocrysts exceeds that of the plagioclase. The groundmass is composed of K-feldspars, plagioclase, quartz and mafic minerals as well as accessory allanite, Fe-Ti oxides, zircon and apatite. Chlorite, titanite, epidote, sericite and calcite are the common secondary minerals. The large anhedral K-feldspars tablets enclose small plagioclase, biotite and hornblende crystals forming a poikilitic texture. Sometimes, the K-feldspar phenocrysts are mantled by plagioclase giving rise to rapakivi texture (Fig. 4B). The K-feldspar core of the rapakivi texture has a smooth rounded outline with clear signs of resorption. Plagioclase occurs as subhedral tabular crystals or as small grains in the groundmass. Sometimes, it develops myrmekitic texture next to K-feldspars in the groundmass. Quartz occurs as anhedral crystals in the groundmass and as intergrowths with feldspars, but rarely as phenocrysts. The mafic minerals are confined mainly to the groundmass and rarely occur as microphenocrysts. They are represented by biotite and less commonly hornblende which are slightly altered to chlorite and iron oxides.

Mafic microgranular enclaves (MME)

They are fine grained and characterized by an equigranular texture (average grain size ~0.5 mm across); sometimes featuring chilled margins indicative of rapid cooling. MME consist mainly of plagioclase, biotite and hornblende with variable amounts of opaques, quartz, K-feldspars and apatite. It contains large plagioclase and K-feldspar xenocrysts having ovoid shape and/or irregular outlines indicating resorption under disequilibrium conditions. The feldspars xenocrysts were derived from the partly crystallized granitic magma and were resorbed through immersion in the more basic magma. They show a spongy cellular texture due to the dissolution of these crystals by the mother enclave magma. Rarely, mafic minerals in the MME are aligned parallel to the contact between the enclaves and their host rocks, providing evidence that the MME were once mafic globules (Vernon, 1991).

Alkaline suite

Katherina Volcanics

They are represented by rhyolite and fallout pyroclastics. Rhyolite is typically spotted with phenocrysts of quartz and alkali feldspars. Rare phenocrysts of biotite and alkali amphibole are observed (Fig. 4C). The phenocrysts are set in a microcrystalline groundmass showing micrographic and spherulitic textures. The fallout pyroclastics cover the entire spectrum from coarse pyroclastic breccias to fine (ash) tuffs; lapilli-, lithic-, crystal-, and banded tuffs are present.

A-type granites

A-type granites comprise syenogranite and alkali feldspar granite. Syenogranite is medium- to coarse-grained with a hypidomorphic equigranular texture. It is composed mainly of K-feldspars, quartz, plagioclase and biotite. Zircon, apatite and iron oxides are accessories, while chlorite, epidote and calcite are secondary minerals. Alkali feldspar granite is medium to coarse grained and characterized by inequigranular texture. It is composed of K-feldspar, quartz and little plagioclase and biotite. The alkali feldspars are the most common mineral and represented by orthoclase perthite and microcline-perthite. The type of perthite ranges from the finely veined to the coarsely patchy type. Quartz occurs as anhedral sutured crystals showing undulatory extinction as well as small interstitial crystals. Plagioclase is represented by albite that occurs as subhedral lath-shaped crystals. Biotite occurs as thin subhedral flakes of brown colour and contains zircon inclusions. It is slightly or completely altered to chlorite. The accessory minerals are represented by Fe-Ti oxides, sphene, zircon and epidote. The pegmatitic pockets in the alkali feldspar granite are coarse grained and composed of quartz, orthoclase, microcline-perthite and rare biotite.

GEOCHEMISTRY

Analytical techniques

All the analyzed samples were carefully chosen after petrographical study to select only fresh samples. Both major and selected trace elements were determined by X-ray fluorescence spectrometry. Concentrations of the major elements were obtained on fused discs, while the trace elements were determined on pressed pellets. The precision was generally better than ±5% for major oxides and must of the trace elements as indicated by the duplicate analyses of rock standards. The concentrations of the REE were determined by inductively coupled plasma spectrometry (ICP-Optima 4300 DV). Loss on ignition (L.O.I.) was determined by heating powdered samples for an hour at 1000 ºC. All the chemical analyses were carried out at the Saudi Arabia Geological Survey, Jeddah, Saudi Arabia.

Major and trace elements

Major and trace elements contents for 25 representative samples of the plutonic and volcanic rocks are reported in Tables 2 and 3. The studied intrusive rocks are plotted on the R_1-R_2 diagram (De la Roche et al., 1980), where the plutonic rocks of the calc-alkaline suite are plotted in the diorite, quartz-monzonite and granite fields, except one sample is plotted in the tonalite field (Fig. 5). On the same diagram, the A-type granites plotted within alkali granite field. On the SiO_2 vs. Zr/TiO_2 classification diagram for the volcanic rocks (Fig. 6), the Rutig Volcanics are plotted within rhyodacite-dacite field (except one sample plotted in the andesite field), while the Katherina Volcanics straddle the boundary between rhyolite and comendite/pantellerite fields. The quartz-diorite and Rutig Volcanics have medium- to high-K character, while the other rock types display the high-K character (Le Maitre et al., 1989; Fig. 7).

Harker diagrams have been constructed for some major and trace elements (Figs. 8 and 9). The variation diagrams show different trends of evolution indicating different magma series. On these variation diagrams, the Rutig Volcanics are more akin to the trend of quartz-diorite, while the Katherina Volcanics follow the same trend of A-type granites. The quartz-diorite and Rutig Volcanics display regular variation trends of decreasing TiO_2, Fe_2O_3, MgO, CaO, Sr, Ni and Cr with increasing silica. On the other hand, K_2O, Rb and Nb increase with increasing silica. Few scatter and subparallel trends on the variation diagrams of Rutig Volcanics and quartz-diorite may be due to the porphyritic nature of the Rutig Volcanics (Cox et al., 1979). The quartz-monzonite and monzogranite display irregular variation trends in most of the major and trace elements, which can be attributed to the effect of magma mixing in this stage. The highest P_2O_5 contents (0.21 to 0.46 wt. %) are observed in the quartz-monzonite. The origin of high P_2O_5 content in magmatic rocks would be multiple, but usually is controlled by source composition and partial melting conditions (Bea et

TABLE 2 | **Chemical composition of plutonic rocks of Wadi Sibaiya.**

Sample	Calc-alkaline suite												Alkaline suite					
	Quartz-diorite					Quartz-monzonite				Monzogranite			Syenogranite				Alkali feldspar granite	
	QD-1	QD-2	QD-3	QD-4	QD-5	QMZ-1	QMZ-2	QMZ-3	QMZ-4	Mon-g-1	Mon-g-2	Mon-g-3	Sg-2	Sg-3	Sg-4	Sg-5	Ag-1	Ag-6
SiO_2	56,98	58,52	58,91	61,21	60,92	64,32	66,46	68,16	65,61	69,67	73,2	69,46	74,38	73,96	75,2	71,9	75,08	75,19
TiO_2	1,1	0,83	0,71	0,67	0,69	0,89	0,53	0,41	0,69	0,36	0,29	0,26	0,23	0,19	0,22	0,25	0,21	0,09
Al_2O_3	17,43	16,6	16,31	15,43	16,91	15,96	16,3	16,01	14,8	14,11	13,84	14,18	13,41	13,75	12,52	14,62	12,01	11,76
Fe_2O_3	7,1	6,67	6,5	5,28	4,89	2,11	1,66	2,02	3,01	1,91	1,62	2,04	1,88	1,95	2,21	2,48	2,44	2,21
MnO	0,17	0,12	0,11	0,12	0,11	0,07	0,03	0,06	0,15	0,03	0,04	0,02	0,01	0,04	0,06	0,11	0,02	0,09
MgO	3,99	3,39	3,51	2,99	3,1	1,68	0,67	0,51	1,29	0,31	0,25	0,31	0,19	0,29	0,21	0,31	0,23	0,21
CaO	6,17	5,46	5,11	4,91	4,65	1,99	1,61	1,13	1,91	1,34	0,96	1,09	0,33	0,46	0,25	0,52	0,23	0,2
Na_2O	3,91	3,76	4,01	3,42	4,11	3,71	3,61	5,01	4,02	4,83	4,59	4,11	3,76	3,96	4,01	4,11	4,31	4,6
K_2O	1,89	1,62	1,59	2,1	2,76	4,89	4,64	4,96	3,99	4,99	4,13	4,76	4,66	4,51	4,51	5,06	5,02	4,73
P_2O_5	0,21	0,23	0,19	0,13	0,14	0,46	0,35	0,21	0,29	0,11	0,09	0,06	0,04	0,08	0,01	0,05	0,02	0,03
LOI	1,85	2,9	1,91	3,01	2,01	2,13	1,89	0,82	2,37	2,58	1,25	2,55	0,62	1,13	1,38	0,56	0,4	0,65
Total	100,8	100,1	98,86	99,27	100,3	98,21	97,75	99,3	98,13	100,2	100,3	98,84	99,51	100,3	100,6	99,97	99,97	99,76
Rb	29	36	40	57	49	89	127	141	101	101	139	112	206	204	215	216	330	349
Ba	989	670	579	759	632	997	698	532	926	832	698	859	134	118	112	206	65	87
Sr	708	581	481	405	410	537	401	372	441	321	202	267	36	57	41	67	29	53
Nb	2	4	5	7	8	10	14	16	12	13	17	13	25	29	31	29	47	56
Zr	149	166	176	136	179	206	199	201	211	192	213	196	187	170	196	185	178	126
Cr	159	140	123	96	73	82	51	42	76	46	29	44	32	60	51	67	10	30
Ni	76	69	54	31	42	31	25	28	39	54	39	49	11	16	13	26	3	9
Zn	56	67	81	51	68	46	51	39	62	38	24	16	36	57	68	78	16	70
Y	15	19	21	17	18	23	20	18	26	18	18	21	34	41	35	35	49	51
V	106	117	119	98	67	62	31	26	56	30	25	19	7	5	8	15	5	11
Co	17	21	16	28	12	6	10	8	11	5	3	6	1	6	3	6	1	9
Pb	43	86	38	26	34	16	49	32	27	74	29	44	14	29	39	59	26	82

TABLE 3 | **Chemical composition of volcanic rocks in Wadi Sibaiya.**

Sample	Rutig Volcanics				Katherina Volcanics		
	R-1	R-2	R-4	R-7	K-1	K-3	K-8
SiO_2	61,33	63,72	63,69	63,45	73,96	76,44	74,51
TiO_2	0,79	0,7	0,55	0,61	0,19	0,18	0,23
Al_2O_3	14,49	15,89	18,03	17,94	11,36	10,81	11,38
Fe_2O_3	6,11	5,27	3,83	3,17	2,57	2,98	3,09
MnO	0,21	0,07	0,07	0,1	0,04	0,02	0,04
MgO	2,49	2,08	1,87	1,85	0,37	0,16	0,18
CaO	5,31	4,31	3,05	2,96	1,29	0,31	0,46
Na_2O	4,84	4,49	4,18	4,03	3,34	3,49	3,16
K2O	2,37	2,13	3,33	3,01	4,8	4,69	5,71
P_2O_5	0,21	0,18	0,19	0,2	0,03	0,01	0,02
LOI	1,21	1,01	0,99	2,14	2,88	0,4	0,97
Total	99,36	99,85	99,78	99,46	100,83	99,49	99,75
Rb	79	77	61	87	192	169	142
Ba	827	699	516	712	238	79	96
Sr	395	379	454	346	50	34	42
Nb	12	10	14	16	43	56	47
Zr	216	193	249	247	546	736	611
Cr	141	109	123	122	13	5	7
Ni	57	27	33	22	9	6	16
Zn	159	79	104	195	52	102	121
Y	26	19	27	28	49	61	53
V	99	81	64	30	8	4	3
Co	22	9	14	16	3	1	2
Pb	195	122	53	95	96	29	36

al., 1992). It is more likely that P_2O_5, incompatible in mafic magmas, increased up to quartz-monzonite composition in which apatite began to precipitate. Hence, the decrease of P_2O_5 became compatible in the felsic magmas (in monzogranite). The alkaline suite forms a single group with almost complete compositional overlap, except the Katherina Volcanics contain the highest Zr contents. In this group, the syenogranite is distinctive by lower concentrations of Rb, Y and Nb than alkali feldspar granite.

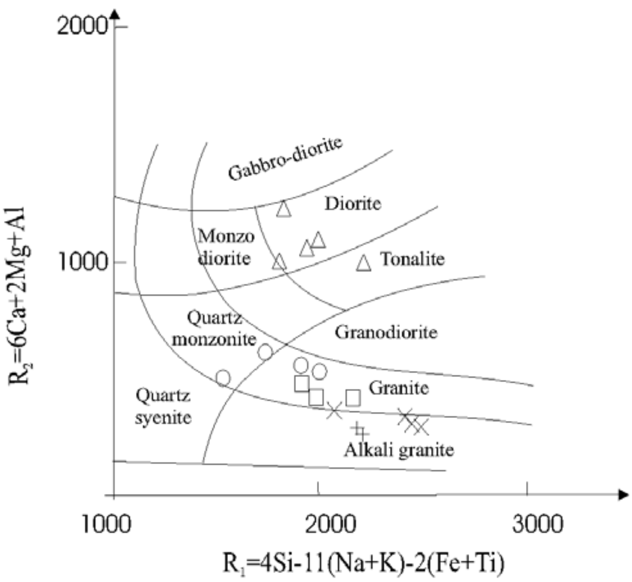

FIGURE 5 | **Nomenclature of the plutonic rocks using R_1-R_2 diagram (De la Roche et al., 1980). See legend in Figure 3.**

The felsic rocks are plotted on discriminant diagram of Pearce et al. (1984), designed to distinguish between granites of various tectonic settings. On this diagram (Fig. 10), the calc-alkaline suite plot in the volcanic-arc field, while the Katherina Volcanics and A-type granites plot in the within-plate field and/or straddle the boundary between the within-plate and volcanic-arc fields. The quartz-monzonite and monzogranite (with SiO_2>68 wt. %) are plotted in the highly fractionated calc-alkaline granite field on the diagram designed by Sylvester (1989; Fig. 11), while the Katherina Volcanics and A-type granites are plotted mainly in the alkaline field. Eby (1992) differentiated the A-type granites into A_1 and A_2 subgroups. A_1 is characterized by element ratios similar to those for ocean-island basalts and emplaced in anorogenic settings such as continental rifts or other intra-plate tectonic settings, while A_2 is derived from melting of a continental crust and may be emplaced in a variety of tectonic environments. The Katherina Volcanics are plotted within A_1 field, while syenogranite and alkali feldspar granite plotted in A_2 field, but very close to the field of A_1 (Fig. 12). Accordingly, the Katherina Volcanics may be derived from mantle source with crustal contribution, whereas syenogranite and alkali feldspar granite are derived mainly from crustal source.

The plutonic rocks at Wadi Sibaiya are normalized to the primitive mantle using the normative values of

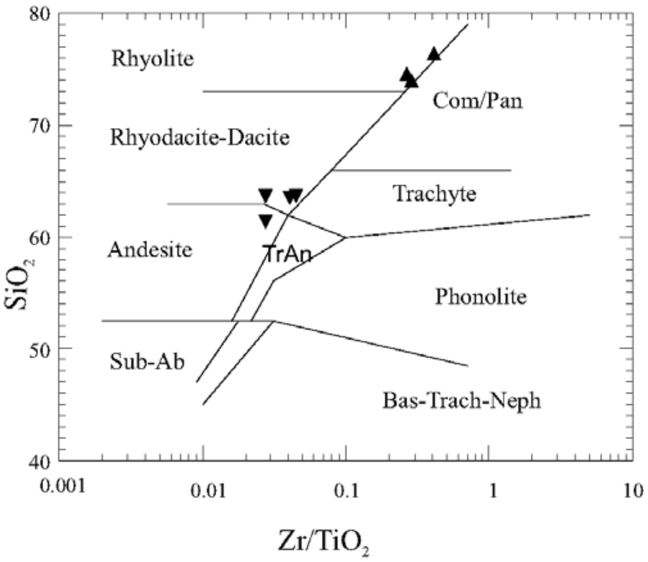

FIGURE 6 | **SiO_2 vs. Zr/TiO_2 diagram showing the classification of volcanics rocks (Winchester and Floyd, 1977). Symbols of the volcanic rocks used in all the given figures are: ▼ = Rutig Volcanics; ▲ = Katherina Volcanics.**

McDonough et al. (1991) and shown in Fig. 13A. The A-type granites are relatively depleted in Sr, P, Eu and Ti and enriched in the highly incompatible elements. The depletion in Sr and Eu are presumably related to the fractionation of feldspars or their retention in the refractory minerals resistant to melting in the lower crust, while the depletion in P and Ti are controlled by the fractionation of apatite and Fe-Ti oxides, respectively (Green, 1980; Bevins et al., 1995). Also, the primitive mantle normalized patterns for the averages of the volcanic rocks are given in Fig. 13B. It is clear that the pattern of Rutig Volcanics is similar to that of quartz-diorite, while the pattern of the Katherina volcanics is similar to that of A-type granites. Therefore, the Rutig Volcanics may be representing the volcanic equivalent of quartz-diorite, while the Katherina Volcanics are the equivalent of A-type granites, especially alkali feldspar granite.

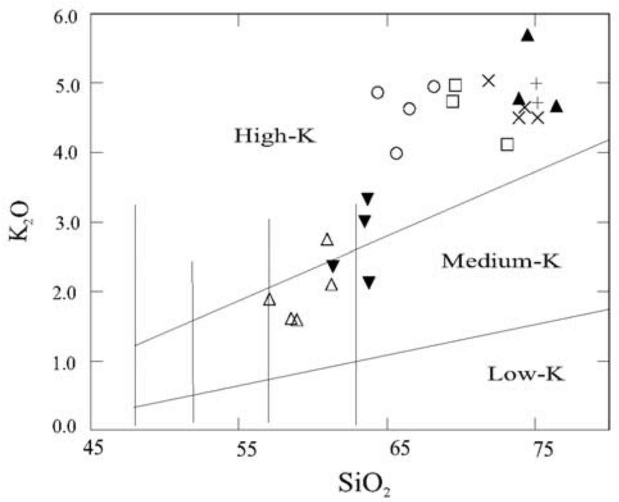

FIGURE 7 | **K_2O vs. SiO_2 diagram for the calc-alkaline and alkaline suites (Le Maitre et al., 1989). See legend in Figures 3 and 6.**

Rare Earth elements (REE)

REE analyses for seven representative samples of plutonic and volcanic rocks are given in Table 4. Quartz-diorite contains the lowest total REE content (∑REE = 89.54) among the intrusive rocks, while the Rutig Volcanics have the lowest total REE contents (∑REE=80.79) among the extrusive rocks. The quartz-monzonite and monzogranite are moderately enriched in REE when compared with the other rock units in the area, while the alkaline suite has higher contents of REE. The highest REE values are observed in the alkaline rhyolite of Katherina Volcanics (∑REE=378.4). The chondrite-normalized REE patterns (using the chondrite values of Evensen et al., 1978) are represented in Fig. 14. The calc-alkaline suite has slight to moderate negative Eu-anomalies [$(Eu/Eu^*)_n$ = 0.65-0.88]. Moderate negative Eu-anomalies indicate slight removal of feldspars from the source melt. The alkaline suite shows pronounced negative Eu-anomaly (Eu/Eu*=0.05-0.30). The strongly negative Eu-anomaly is mostly associated with the low Sr concentrations indicating extreme feldspar fractionation. In general, the relatively pronounced negative Eu-anomaly and enrichment in LREE/HREE in the alkaline suite indicate crystallization from a magma extremely depleted in plagioclase in its most evolved residual liquids.

PETROGENESIS

The difference in the composition of the studied rocks and, consequently, the different magmatic suites involved, is a result of the different tectonic regimes, subduction-related versus extension. The Rutig Volcanics and quartz-diorite represent subduction-related I-type magma, probably generated from anatexis of older crust with contribution of the mantle-wedge magma. The absence of basalt among the Rutig Volcanics and gabbro among the plutonic rocks suggests that the Rutig Volcanics and quartz-diorite produced directly from an intermediate calc-alkaline magma. Partial melting of a subducted oceanic crust can produce calc-alkaline magmas of andesitic composition (Green and Ringwood, 1968; Green, 1980; Gill, 1981). The overall trends of the major and trace elements suggest that the Rutig Volcanics and quartz-diorite evolved from the same magma source which has undergone some degree of magmatic differentiation. Plagioclase and mafic minerals (amphibole and/or biotite) are the main fractionating phase, while apatite and Fe-Ti oxides played a

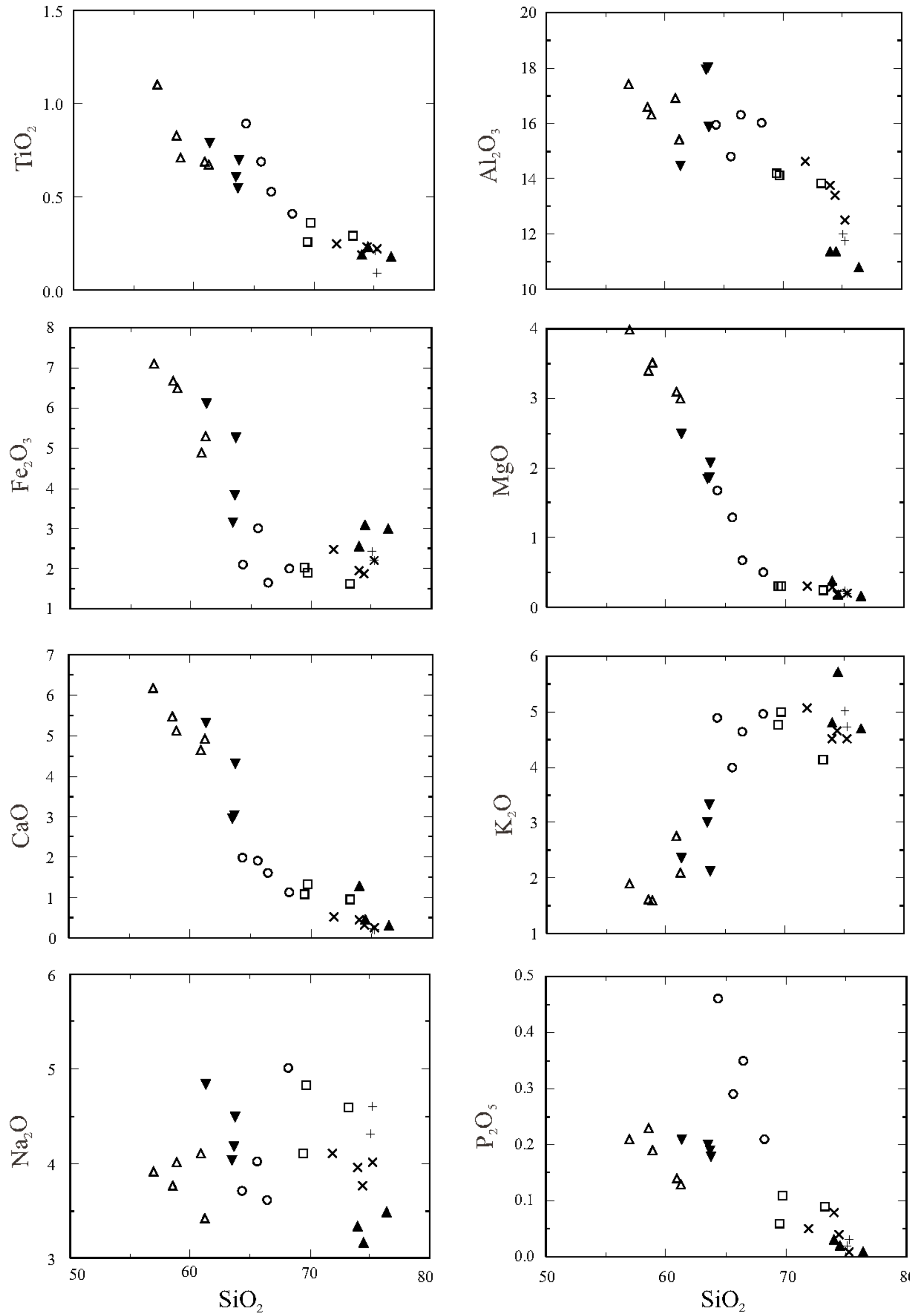

FIGURE 8 | **The relation between SiO_2 and major oxides in the calc-alkaline and alkaline suites. See legend in Figures 3 and 6.**

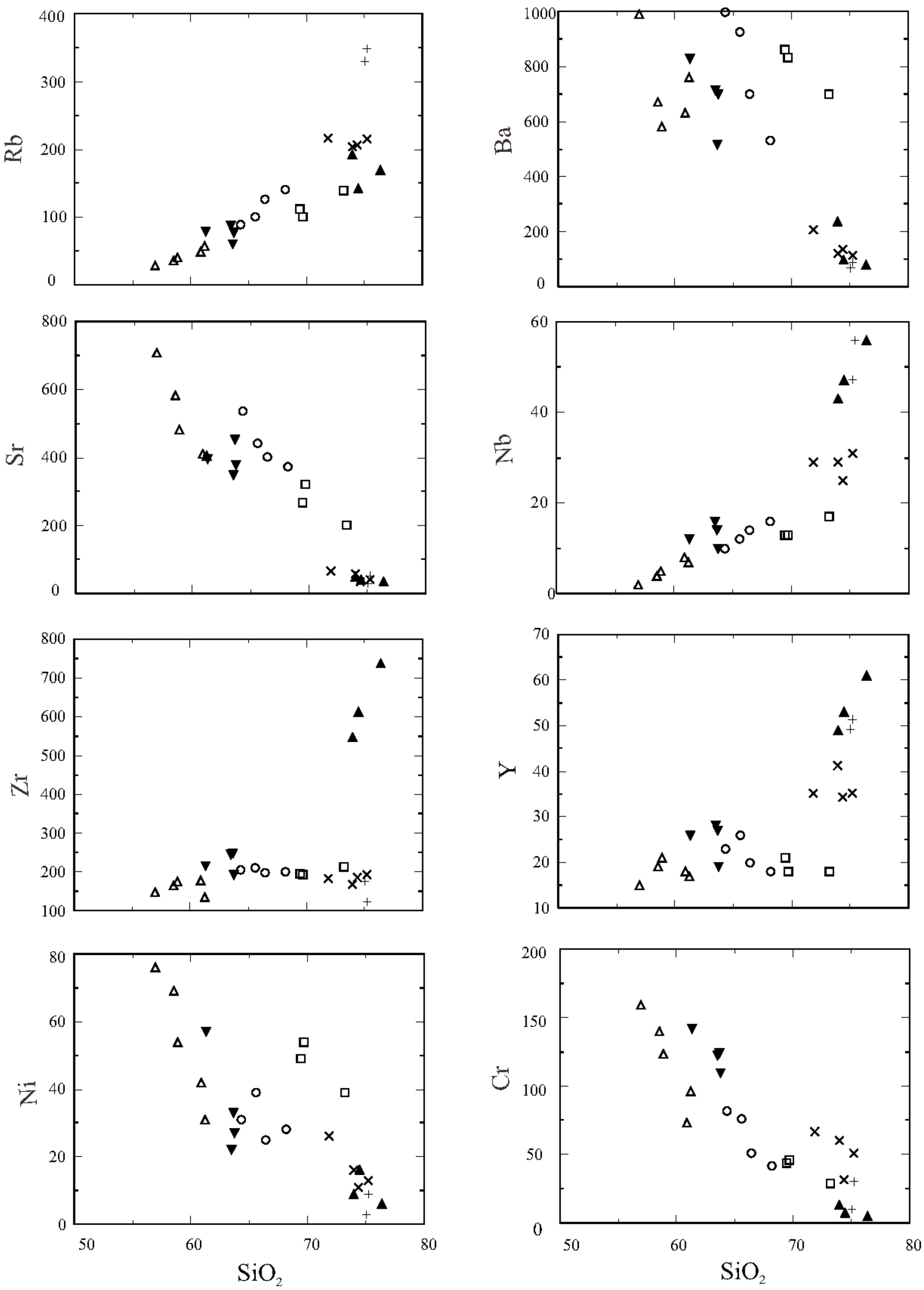

FIGURE 9 | **The relation between SiO_2 and some trace elements in the calc-alkaline and alkaline suites. See legend in Figures 3 and 6.**

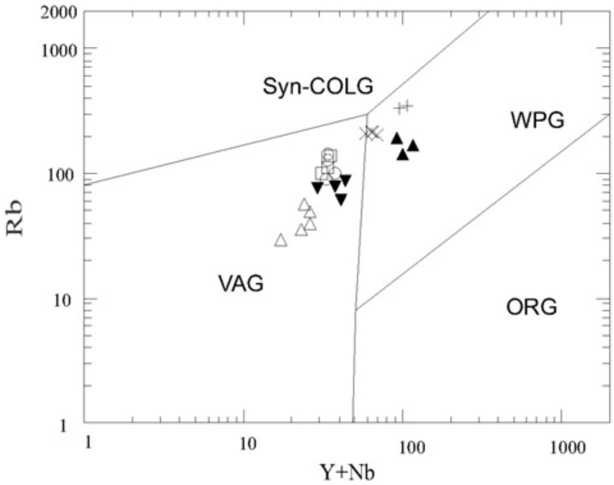

FIGURE 10 | **Rb vs. (Y+Nb) diagram for the studied rocks (Pearce et al., 1984). See legend in Figures 3 and 6.**

minor role. This is consistent with the progressive decrease in CaO, MgO, Fe_2O_3, TiO_2, Sr, Cr and Ni with increasing SiO_2. Few scatter on the variation diagrams of Rutig Volcanics and quartz-diorite may be due to the porphyritic nature of the Rutig Volcanics (Cox et al., 1979).

The available data for the quartz-monzonite and monzogranite can furnish, to some extent, criteria for their petrogenesis. Field relations, macroscopic and mineralogical features and whole rock geochemistry are consistent with a hybrid origin for these rocks due to injection of the partly crystallized granitic magma by more basic melts. The evidences for the magma mixing in this stage is indicated by: a) the presence of mafic microgranular enclaves (e.g. Baxter and Feely, 2002; Arvin et al., 2004; Janousek et al., 2004; Kumar et al., 2004; Barbarin, 2005), sometimes featuring chilled margins indicative of rapid cooling; b) the presence of large feldspar xenocrysts with ovoid shape, spongy cellular texture and resorbed outlines piercing into or engulfed in the enclaves (e.g. Bussy, 1990; Andersson and Eklund, 1994; Arvin et al., 2004); c) the development of rapakivi texture (e.g. Hibbard, 1981, 1991; Bussy, 1990; Andersson and Eklund, 1994; Baxter and Feely, 2002; Slaby and Götze, 2003); d) embayed enclave margins indicative of liquid-liquid contacts; e) complex zonation in the feldspars and apatite; and f) marked variation in some element contents. Also, the irregular variation in most of the major and trace elements for the quartz-monzonite and monzogranite (Figs. 8 and 9) support the effect of magma mixing in this stage. The mineralogical and geochemical characteristics of the quartz-monzonite and monzogranite indicate a mildly alkaline character and belonging to transitional magma type on the borderline between the calc-alkaline and alkaline magma.

The mafic microgranular enclaves (MME) are frequently present in many Egyptian granitoids (El-Ramly, 1972; El-Gaby, 1975; Hussein et al., 1982; Akaad et al., 1996 and others). The presence of such MME in the quartz-monzonite and monzogranite is an indication of heterogeneity and it is clear in the geochemical data. Several models have been suggested for the origin of the MME: a) one of the earliest ideas for the origin of MME is related to a cumulate (e.g. Pabst, 1928; Dodge and Kistler, 1990), but ignores the grain size differences between MME and host granitoids; b) the MME are restite (White and Chappell, 1977; Chappell et al., 1987), and c) the MME represent mafic magma injected in a partly crystallized felsic magma (Vernon, 1984, 1990, 1991; Eberz et al., 1990; Didier and Barbarin, 1991; Baxter and Feely, 2002; Arvin et al., 2004; Janousek et al., 2004; Kumar et al., 2004; Barbarin, 2005). Indeed grain size in MME is smaller compared to the host granitoids suggesting that the MME can not be cumulate of the pluton itself. Meanwhile, restite is an essentially nongenetic designation for all immobile or less mobile parts of migmatites (Bates and Jackson, 1980) which imply that the present MME can not be restite. Field and petrographical observations suggest that the present enclaves represent globules of hotter mafic magma that were incorporated and undercooled against partly crystallized granitic magma. The presence of felsic xenocrysts in MME is the result of the mechanical transfer of mineral grains during magma mixing phenomena (e.g. Pesquera and Pons, 1989). The chemical characteristics of such enclaves are difficult to interpret because most enclaves have undergone chemical modification by hybridization with the felsic magmas (Eberz and Nicholls, 1990; Bogaerts et al., 2003; Bonin, 2004; Tepper and Kuehner, 2004).

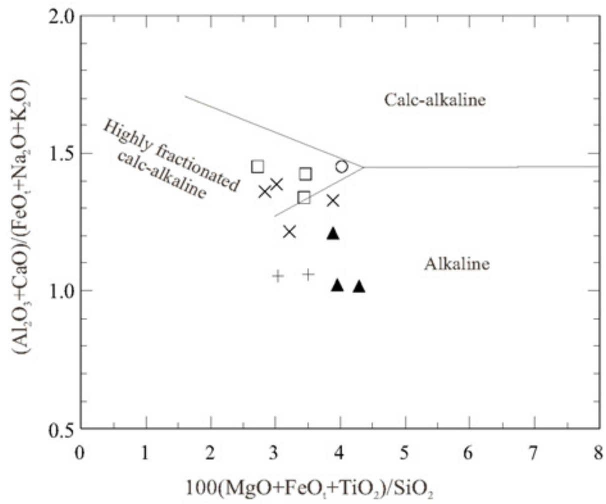

FIGURE 11 | **$(Al_2O_3+CaO)/(FeO(t)+Na_2O+K_2O)$ versus $100(MgO+ FeO_{(t)}+TiO_2)/SiO_2$ diagram (Sylvester, 1989). See legend in Figures 3 and 6.**

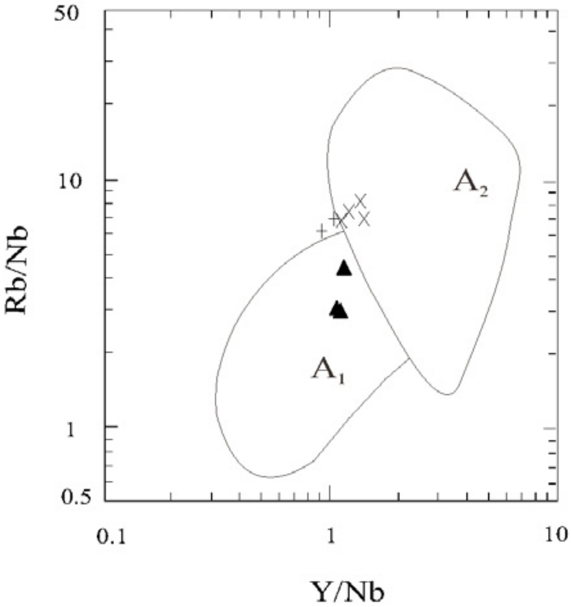

FIGURE 12 **Rb/Nb vs.Y/Nb diagram for distinction of A-type granitoids (Eby, 1992). See legend in Figures 3 and 6.**

The alkali feldspar megacrysts in the quartz-monzonite and monzogranite usually show rapakivi texture and are rarely zoned. The association of rapakivi texture with the mafic microgranular enclaves confirms the genetic link between the rapakivi texture and magma mixing (Bussy, 1990). Such process involves partial dissolution of the K-feldspars megacrysts prior to the formation of the plagioclase mantle (Stimac and Wark, 1992). Several interpretations have been suggested for the origin of the rapakivi texture: a) due to basification of partly crystallized magma by assimilation of andesitic rocks (Williams et al., 1958; b) as a reflection of the reduction of pressure accompanying the emplacement of magma (Cherry and Trembath, 1978; Nekvasil, 1991); c) due to differences in the stability of anorthite as a function of the fluorine activity of the melt (Price et al., 1996); and d) mingling-mixing of basic magma with felsic magma (Hibbard, 1981, 1991; Andersson and Eklund, 1994; Baxter and Feely, 2002; Slaby and Götze, 2003). The genesis of the rapakivi texture in the present study can be attributed to magma mixing due to the association of rapakivi texture with mafic microgranular enclaves.

The studied alkaline suite, including Katherina Volcanics, syenogranite and alkali feldspar granite, has petrographical and geochemical characteristics of A-type magma. Magma with A-type geochemical characteristics could be generated through several processes (Whalen et al., 1987; Eby, 1990, 1992). A variety of petrogenetic models have been proposed for the A-type alkaline magmatism. The distinctive features of many A-type magmas, like high temperature, relatively anhydrous nature, and low initial $^{87}Sr/^{86}Sr$ ratios, led many workers to accept a mantle origin without a significant crustal contribution (e.g. Bonin and Giret, 1985; Turner et al., 1992). Others considered the A-type suites as anatectic melts of various crustal sources, which include granulitic lower crust (Collins et al., 1982; Chappell et al., 1987), charnokitic lower crust (Landenberger and Collins, 1996), or tonalitic crust (Cullers et al., 1981; Creaser et al., 1991). Stoeser and Elliott (1980) proposed a petrogenetic model for the A-type suites involving their generation through fractionation of I-type melts, while Whalen et al. (1987) and Sylvester (1989) believe that A-type melts were derived from older rocks from which an I-type melt had been extracted earlier. However, Sylvester (1989) admits that the origin of the high temperatures necessarily for melting remain unsolved. The geochemical characteristics of the Katherina Volcanics indicate that they derived from mantle source with crustal contribution. Low Ba, Sr, Cr and Ni contents in the syenogranite and alkali feldspar granite indicate that they are representing residual melts derived from deeper magma chamber through extreme crystallization process.

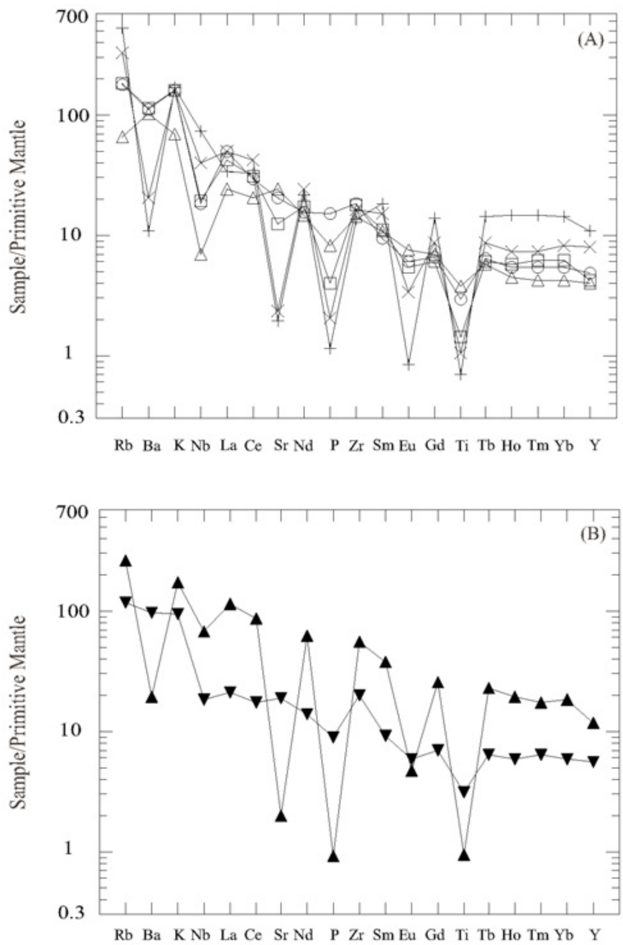

FIGURE 13 **A) Primitive mantle-normalized spider diagram for the plutonic rocks. B) Primitive mantle-normalized spider diagram for the volcanic rocks. See legend in Figures 3 and 6.**

TABLE 4 | **REE concentrations of the representative samples in Wadi Sibaiya.**

Sample	Calc-alkaline suite				Alkaline suite		
	QD-5	QMZ-2	Mon-g-3	R-1	Sg-2	Ag-6	K-8
La	17,10	35,60	30,30	15,00	35,6	24,2	81,10
Ce	38,20	54,10	57,00	32,10	78,5	61,1	161,00
Nd	20,00	21,30	24,00	19,00	33,0	30,0	86,00
Sm	4,80	4,19	5,00	4,10	6,7	8,2	17,00
Eu	1,28	1,01	0,90	1,00	0,6	0,1	0,80
Gd	4,10	3,88	3,60	4,10	5,1	8,2	15,10
Tb	0,61	0,69	0,65	0,70	0,9	1,6	2,50
Ho	0,73	0,90	0,95	0,97	1,2	2,4	3,20
Tm	0,31	0,40	0,46	0,47	0,5	1,1	1,30
Yb	2,10	2,70	3,10	2,90	4,0	7,0	9,10
Lu	0,31	0,40	0,49	0,45	0,6	1,1	1,30
Sum	89,54	125,17	126,45	80,79	166,67	144,96	378,4
$(Eu/Eu^*)_n$	0,88	0,77	0,65	0,75	0,30	0,05	0,15
$(La/Sm)_n$	2,30	5,49	3,91	2,36	3,44	1,90	3,08
$(Gd/Lu)_n$	1,63	1,20	0,91	1,13	1,13	0,97	1,44
$(La/Lu)_n$	5,91	9,54	6,63	3,57	6,77	2,47	6,69

The available initial $^{87}Sr/^{86}Sr$ ratios for some rock types in the studied area after Bielski (1982) are 0.7045±0.0005 for Rutig Volcanics, 0.7047±0.0012 for Katherina Volcanics and 0.7062±0.0013 for alkali feldspar granite. The increase of initial $^{87}Sr/^{86}Sr$ ratios from the oldest to youngest rocks indicates increasing involvement of crustal rocks in the generation or modification of these rocks with age.

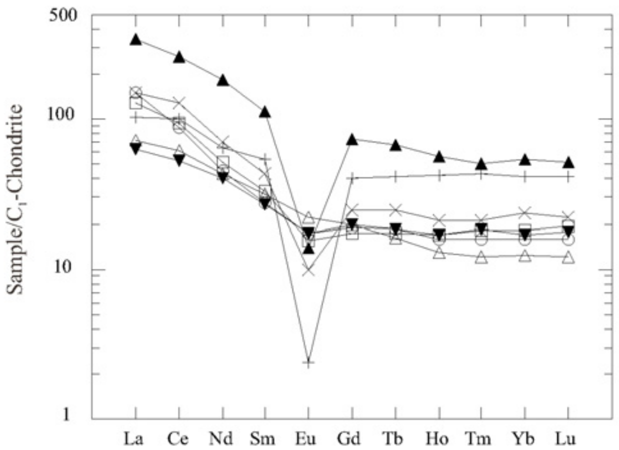

FIGURE 14 | **Chondrite-normalized REE patterns for the studied rocks. See legend in Figures 3 and 6.**

CONCLUSIONS

The chronological sequence of the different rock units in the mapped area starts with emplacement of Rutig Volcanics and quartz-diorite during the late phase of the Pan-African orogeny. This was followed by the intrusion of quartz-monzonite and monzogranite. Afterwards, extrusive Katherina volcanics were erupted and A-type granite was intruded. The rock units in the studied area can be grouped into two petrotectonic assemblages, with a calc-alkaline suite and an alkaline suite. The former includes Rutig Volcanics, quartz-diorite, quartz-monzonite and monzogranite, while the latter includes Katherina Volcanics, syenogranite and alkali feldspar granite. Based on the field relations and available age dating, the Rutig Volcanics are the oldest rock unit in the studied area. The microscopic studies indicate that the lower unit of these volcanics was subjected to low-pressure metamorphism in the greenschist facies. The metamorphosed volcanics have the following mineral assemblages: plagioclase + biotite + epidote + chlorite + opaques ± actinolite ± quartz. The textural features displayed by the quartz-diorite (kink, decussate and foliated textures) reveal that it was subjected to deformation and thermal metamorphism. The geochemical characteristics of the Rutig Volcanics and quartz-diorite suggest that these rocks were generated in a volcanic-arc setting from partial melting of the mantle wedge above the subduction-zone with contribution of continental crust.

The MME in the quartz-monzonite and monzogranite represent globules of hotter mafic magma that were incorporated and undercooled against partly crystallized granitic magma. The association of rapakivi texture with the MME confirms the genetic link between the rapakivi texture and magma mixing. The present study revealed that the Katherina Volcanics and A-type granites are emplaced in within-plate tectonic setting. The former is derived from mantle source with crustal contribution, while the latter represents residual melts derived from deeper magma chamber through extreme fractional crystallization process.

The large differences in REE concentrations between the different rock types in the present area support independent magma sources. The Rutig Volcanics and quartz-diorite contains the lowest REE contents and show a smooth and gently slopping REE pattern with a slight negative Eu-anomaly. Meanwhile, the REE patterns of the quartz-monzonite and monzogranite are uniform, parallel to sub-parallel, and LREE fractionated. They show moderate light REE enrichment, rather flat heavy REE patterns and moderately negative Eu-anomalies. Alkaline suite contains the highest REE contents and shows strong negative Eu-anomaly [$(Eu/Eu^*)_n$= 0.05-0.30]. Negative Eu-anomalies in the alkaline suite are mostly associated with low Sr indicating extreme feldspar fractionation.

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